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... WITHOUT RIGHT ANGLE.

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Abstract. *Currently sculptural design is one of the most discussed themes in architecture. Due to their light weight, easy transportation and assembly, as well as an almost unlimited structural variety, parameterised spatial structures are excellently suited for constructive realisation of free formed claddings. They subdivide the continuous surface into a structure of small sized nodes, straight members and plane glass panels. Thus they provide an opportunity to realise arbitrary double-curved claddings with a high degree of transparency, using industrial semi-finished products (steel sections, flat glass). Digital design strategies and a huge number of similar looking but in detail unique structural members demand a continuous digital project handling. Within a research project, named MYLOMESH, a free-formed spatial structure was designed, constructed, fabricated and assembled. All required steps were carried out based on digital data. Different digital connections (scripts) between varying software tools, which are usually not used in the planning process of buildings, were created. They allow a completely digital workflow. The project and the above-mentioned scripts are described in this paper.*

1 INTRODUCTION

During the past 15 years geometry became increasingly important in architectural design. Based on powerful hardware components and a new generation of CAD- respectively modelling-software tools, more and more amorphously formed buildings are being designed. Due to technical problems related to the realisation of double curved surfaces and the usually unique character of architectural design it is very sophisticated to build them.

In this context spatial structures come to the fore. If their members are of varying length, they are adaptable to arbitrary double curved forms. Spatial structures allow facades with a high degree of transparency. Simultaneously they subdivide the mostly extensive envelope and generate a system of individualised, relatively small sized elements. The benefits of standardised spatial structures like the ability to prefabrication, easy transportation and assembly still persists. An often huge number of structural members look similar on the whole but become individual in detail. Such spatial systems can be characterised as parameterised.

Mostly different, partially not architectural software tools are used in early design phases to create the free form. They generate a lot of geometrical data to describe the surface and the mesh, which depends on it. Furthermore these data define the basis for the subsequent geometric-constructive structural design. For the realisation of such parametric spatial stuctures under economic conditions it is absolutly necessary to warrant a digital workflow from the design of the form to the fabrication and assembling of the devices.

To explore the digital workflow from start to finish the MYLOMESH-project was launched. Different small software tools (scripts) were created to analyse the geometry of the mesh and to connect the varying ”standard software tools”, like MICROSOFT EXCEL and AUTOCAD. Inspired by the table lamp MYLONIT by IKEA (Fig. 1) the realisation of its completely double curved shape in an abstract form at a tenfold scale was the aim of the project. Thus MYLOMESH represents a sculptural, free-formed, parametric spatial structure.

Figure 1: Original MYLONIT table lamp

2 THE MYLOMESH PROJECT

2.1 Reproduction and meshing

The first design step was the reproduction of the table lamp geometry in a digital, three-dimensional model. Thereby the requirements to geometrical correctness were relatively low, thus photogrammetrical or laserscanning techniques are not needed. The question to be responded was: ”How to reproduce the double curved shape of the lamp - geometrical completely, whith little expenses, by using the computer?” A decision was reached in favour of RHINOCEROS, a 3D modeling and rendering program for MICROSOFT WINDOWS. It is an inexpensive tool, which is easy to learn and to handle. All geometrical elements were completely described as NURBS-objects. Based on a IKEA catalogue photo two plane splines and two also plan, but spatial rotated circles were defined. They describe the lateral edges of the lamp in front view and their bottom and top surface. Afterwards the surface of the lamp was generated quickly and simple by using an software internal command.

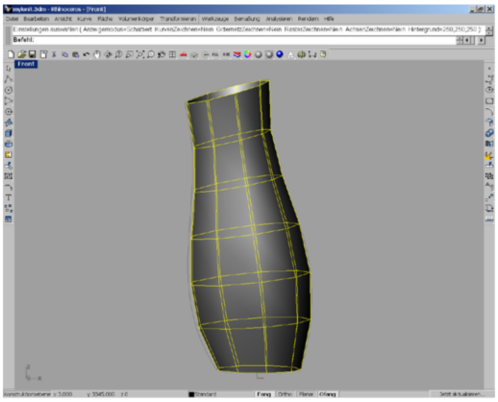

Figure 2: Digital MYLONIT table lamp with quadrangular surface mesh

In the following design step the double curved surface was meshed. For this task also a functionality of RHINOCEROS was used, which applies a mesh to a NURBS-defined surface. Due to variable parameters in the control mode of the so called ’mesh generator’ the tightness of the mesh and thus the degree of abstraction of the continuous double curved surface can be varied.

This operation is of particular importance. First, the number of components which have to be fabricated and assembled depends on it. Second, the way of meshing respectively the type of the discrete mesh is vitally important to the mechanical properties and thus to the suitability as a load bearing system. Third, meshing is of direct influence to the appearance of the structure. In the case of MYLOMESH a quadrangular mesh with 63 nodes and 114 edges was selected from several alternatives (Fig. 2).

The geometrical structure of the mesh and the co-ordinates of the nodes were twice exported by using the considerable export functionality of RHINOCEROS. The generated dwg-file defines the basis for all the construction-related further developements using AUTOCAD. Thus in the subsequent step the quadrangular mesh which is kinematic in plane were transformed to rigid triangular ones by insertation of single diagonals in each discrete mesh. Consequently the number of edges of MYLOMESH increases to 171. The nodal co-ordinates represent the basis for the geometrical analysis of the mesh. For this purpose they were exported as a csv-file for using in MICROSOFT EXCEL .

2.2 Analysing of mesh with respect to construction

The geometry of the surface mesh is completely defined by the unique length of the edges and the variable spatial angles between them. For the construction-related detailing of the structure a construction-related characterisation of the mesh geometry is necessary, which includes the spatial adjustment of members and nodes relative to the surface mesh.

The adjustment of the nodal elements is primarily defined by the so called nodal axis. Different, field-tested approaches for the determination of this were published in [1] [2]. A set of local angles can be identified using positional relations between the individual nodal axis and the ”aligned edges”, which join at one node [2] [3]. Thereby the adjustment of the nodal axis is of vital importance to the values of all the nodal angles an their spreading [4]. Figures 3–5 give a visual review on that topic.

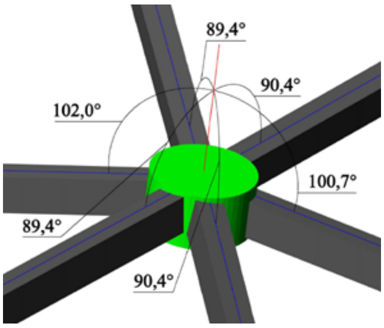

Figure 3: Nodal axis angle

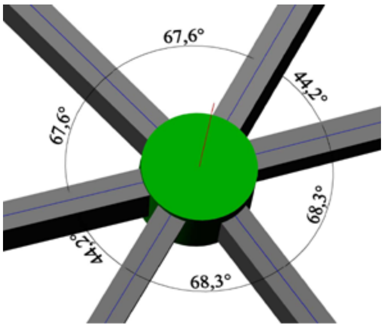

Figure 4: Sector angle

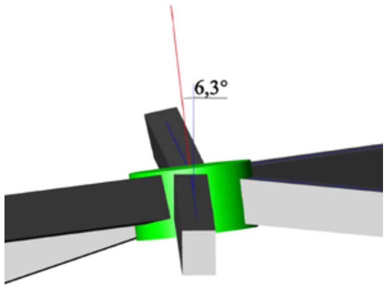

Figure 5: Member-rotating angle

For analysing surface meshes related to construction MESH EXAMINER was developed. This little software tool bases on MICROSOFT EXCEL and Visual Basic for Applications (VBA). It completely calculates global geometry data, like the length of the edges and the spatial angles between them, as well as a set of nodal angles as local geometry data, which directly depend on the adjustment of the nodal axis [5].

2.3 Structural design

The node is the most important element of a spatial structure [6] [7]. It works as an mediator between the members respectively their ends and allows to tie them positively. Furthermore it is the medium which contains a substantial part of the local geometric information. During the structural design process the basic shape and the dimensions of the node have to be defined. Joining technology of the ends of members and nodes by welding or by screwing primarily determines the former, while the individual nodal dimensions depend on two different edge conditions. First, they depend on the shape and size of the cross section of members, which are determined by the way and the rate of loading. And second they depend on the local geometry of the surface mesh, which is based on the way of meshing and the adjustment of the nodal axis.

The MYLOMESH-structure primarily does not satisfy a load bearing function. According to this the circular form of the node was determined under aesthetical criteria and sheet steel as the basic material was selected. The constant dimension of the node bases on research into ”freedom of collision” at all the nodes of the mesh, described above. All the nodes are of equal dimension to take ”optical silence” to the structure. Technological considerations were the basis for the use of sheet metal for the nodal fabrication and for the implemetation of lugs arranged radially around the node to realise the connection between members and nodes. The form of the nodes implies two of three nodal angles. The radial position of the plates specifies the ”Sectoral angle” (Fig.4). The folding of the lugs allows to realise the ”Nodal axis angle” (Fig.3).

The choice of the members cross-section primarily results from aesthetical, less mechanical criteria. Technological considerations were the basis for the use of wood as member material. The unique length of them and the individual slots at both ends of the members, which realise the ”Member-rotating angles” (Fig.5) are also vital elements of the geometrical information of the structure. The connection techology was completly standardised under view points of assembling. To warrant solvability and increased artistic pretensions a joint using book binder screws was defined. After the definition of all constructive parameters the spatial structure was completly digitally modeled (Fig. 6).

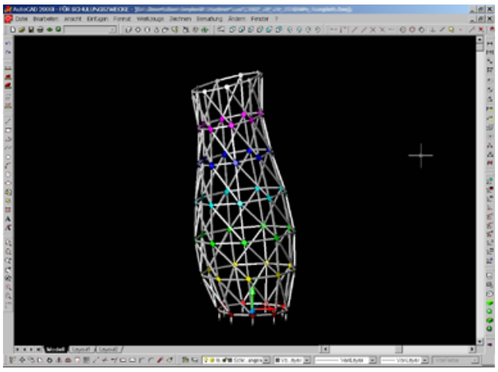

Figure 6: 3d-model of spatial structure

2.4 Generating cutting templates

All the nodes of the amorphously formed structure look similar but are unique in detail. In terms of complete digital project handling it was essential to develope a software tool, which generates the form of the cutting templates based on the geometrical data from mesh analysis.

The corresponding algorithm was programmed as a script in VBA for AUTOCAD. On a form, all the necessary constructive-geometrical basic parameters, which are constant at all nodes, were requested (Fig.7). The individual nodal values of the angles were read out via a ”link” to the EXCEL-file, which contains the results of the mesh analysis. The number of values per node were equivalent with the number of lugs at it. Thus the marginal nodes at the head (4) and at the bottom (5) as well as in the middle of the mesh (6 lugs) can be identified clearly.

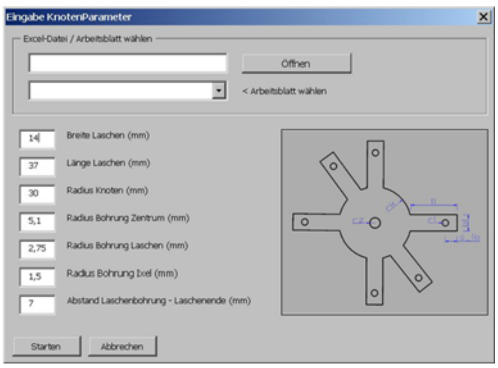

Figure 7: Nodal form

The individual character of all nodes in principle allows to determine each one of them on the basis of his ”lug angles”. In this case the partially very small discrepancies of values mean a formidable handicap. Hence it was important to label the cutting templates in order to smooth processing and assembling. A radial pinhole code system was developed, which bases on the ring-shaped arrangement of the nodes and their position in the ring (Fig.8).

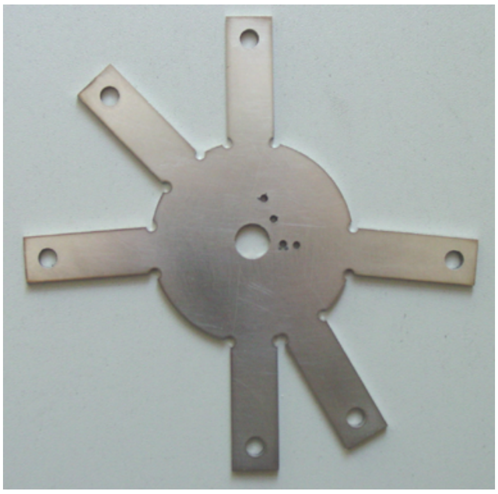

Figure 8: MYLOMESH node

The algorithm generates the nodes consecutively in a AUTOCAD-drawing based on their nodal number. To avoid intersections, the distance between them was adapted dynamically. In terms of minimisation of cut the nodes were translated and rotated on the drawing afterwards. This was made in a field, which is equivalent to the dimension of the sheet metal in fabrication. Figure 9 shows the finished CAD-file.

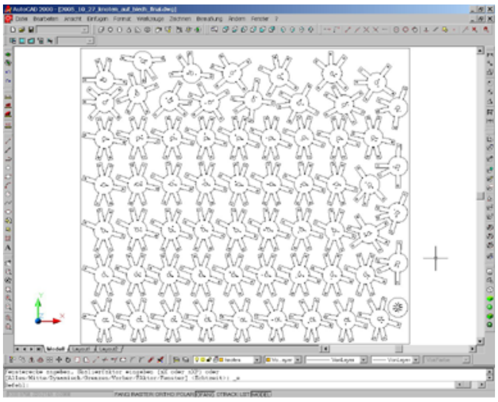

Figure 9: Cutting templates of all nodes

2.5 Fabrication of members and nodes

The starshaped nodes were made of stainless steel. All the essential information for fabrication with the exception of the thickness of 2.5 mm contains the ”drawing” of all 63 cutting templates, described above. In a ”file-to-factory”-process it was directly sent via email from the author to the manufacturer. Without any test all the nodes were cut from a sheet by using a CNC-lasercutter (Fig. 10).

The members of the spatial structure were made of ash wood with a cross-section of 2 x 2 cm. In the production process they have to be tailored to their unique length. Furthermore at both ends also individual, longitudinally rotated slots as well as constant diameter drillholes have to be realised. The members were fabricated in the workshops of the Bauhaus-Universitt Weimar using a CNC machining centre with 5-axis technology for high-speed machining of wood-derived products (Fig. 11). Therefore an algorithm was programmed, which controls an integrated fabrication operation with multiple tool change. The essential, geometric-constructive data were derived from the results of the mesh analysis and transfered by an EXCEL-file.

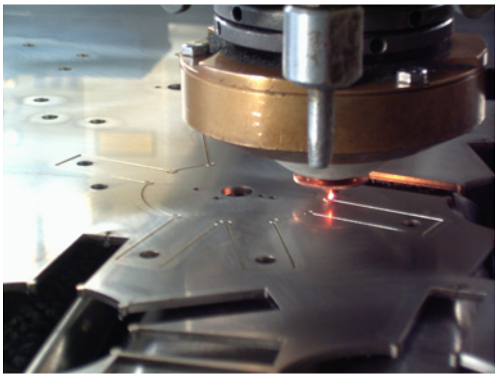

Figure 10: CNC laser cutting of the nodes

Figure 11: CNC machining centre

3 CONCLUSIONS

Recapulating the previous, it can be observed, that the defined project aims were completely reached. A fully parametric spatial structure was developed (Fig. 12). By means of self programmed scripts the data of the digitally modeled basic geometry were manifold transformed and used in different ways. Thereby only inexpensive, easy-to-handle and partially standard office software was utilized. Thus it was possible to analyse the graphical oriented surface mesh related to constructiveness as well as to generate the nodal cutting templates on the basis of the mesh analysis results. All the unique members and nodes were fabricated using CNC-machines.

Figure 12: MYLOMESH in the main building of the Bauhaus-Universitt

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